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Modeling of the turbulent melt flow in metallurgical processes

ABSTRACT

Numerical modeling of the turbulent melt flow, heat and mass transfer in metallurgical processes plays an important role in further improvement of existing technologies and in development of new industrial techniques. The results presented in this paper are carried out using the three dimensional (3D) Large Eddy Simulation (LES) turbulence model. This modeling approach has been validated on experimental data carried out from various induction furnaces. The comparison of numerical and experimental results gave good agreement in case of time-averaged and also for transient flow and temperature distribution in the melt taking into account 3D transient low-frequency flow oscillations, which are mainly responsible for the heat and mass transfer between the main flow eddies. Along various industrial applications, like induction crucible furnace and the cold crucible skull melting process of titanium-aluminum the 3D-LES model is used successfully in order to investigate the time-dependent behaviour of the melt flows, to improve the stability of the process or to study the influence of different design and operation parameters in order to optimize the metallurgical processes.

INTRODUCTION

Industrial metallurgical processes like melting of alloys in induction furnaces has become a subject of modelling and analysis since many years. A wide range of different numerical modelling approaches for the simulation of the turbulent melt flow and the heat and mass transfer processes have been developed. But up to now a universal and always reliable modelling approach which can be used for the development and design of industrial metallurgical applications is not available.

Melting of alloys in induction crucible furnaces can be mentioned as a wide spread example of numerical modeling, because this process can be approximated with two-dimensional (2D) axial-symmetric model. The flow pattern in these installations is formed by the influence of electromagnetic forces and usually comprises of two or more toroidal dominating re-circulating vortices. Flow patterns obtained with two-dimensional solvers based on Reynolds Averaged Navier-Stokes (RANS) equations usually are in good agreement with estimated and measured time-averaged flow velocity values. The resulting spatial distribution of the temperature and alloys compound concentration depends strongly on the heat and mass exchange between vortices of mean flow. Numerical investigations show that two-dimensional turbulence models, e.g. k-ε and others, fail to describe correctly the heat and mass transfer processes between the main vortices.

At the present time, different modelling techniques are being used to achieve better agreement with the experiment [1,2]. Our own engineering approach developed for this problem is described in [3], however, it is necessary to investigate advanced simulation methods for more generic and therefore universal flexible solutions. Due to the permanent growth of accessible high powerful computational resources, nowadays, it is possible to run more complicated transient and three-dimensional (3D) numerical calculations of fluid dynamic problems using advanced turbulent models with higher time and volume resolution requirements and to get reliable results in reasonable time. Concluding all these preconditions the calculations presented in this paper were devoted to the application of Large Eddy Simulation (LES) method for turbulent re-circulating flows, which often occur in various industrial processes where liquid metal is acting by electromagnetic forces.

EXPERIMENTAL SET-UPS AND RESULTS

The experimental investigations of the melt flow velocities and temperature distributions in the melt are carried out in different laboratory induction furnaces like induction crucible furnace (ICF), shown in Figure 1, where Wood´s metal is used as the model melt, and induction furnace with cold crucible (IFCC), shown in Figure 2, where aluminum serves as the model melt. The ICF (Figure 1) has a radius of 158 mm and a height of 756 mm, where the inductor height is 570 mm. Wood's metal, which has a melting point of 72°C, and a dynamic viscosity of $4.2 \cdot 10^{-3}$ kg/m·s, a density of 9,700 kg/m^3 and a conductivity of $1 \cdot 10^6$ S/m was used as a model melt. Potential difference velocity probe with incorporated permanent magnet [4] is used to measure simultaneously two velocity’s mponents with scanning rate from 20 up to 100 Hz.

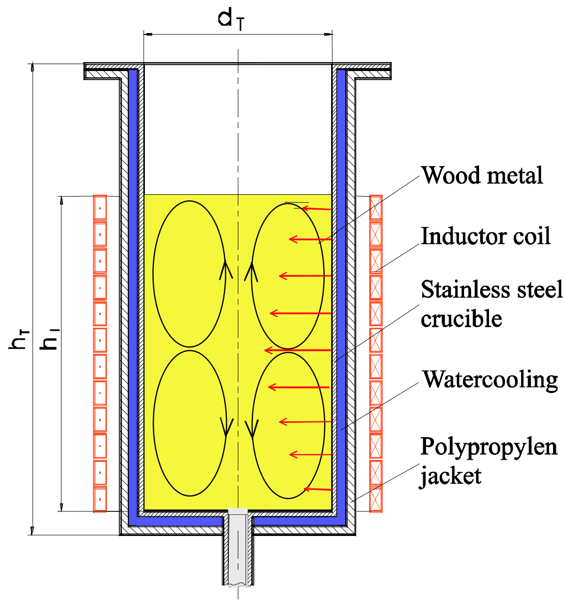

Figure 1: Laboratory induction crucible furnace with sketch of typical Lorentz force distribution and vortexes of mean flow

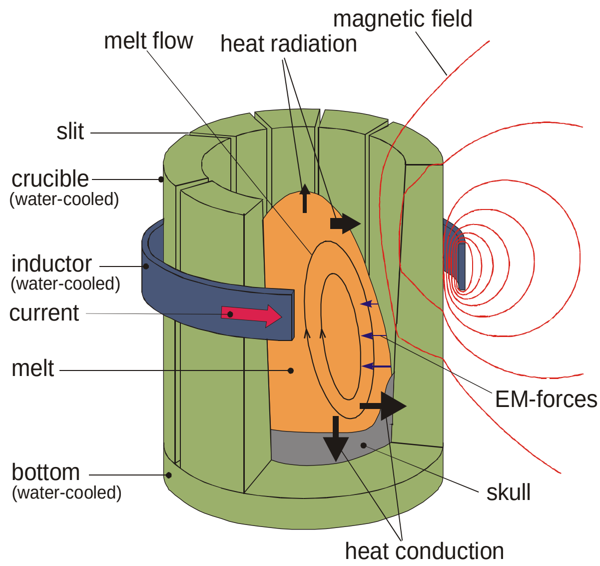

Figure 2: Sketch of the induction furnace with cold crucible with typical melt flow and heat flux distribution

The water-cooled crucible wall keeps the melt temperature at the constant level slightly above 80˚C, therefore thermal gradients are negligible and have no influence on the melt properties. The flow pattern measured consists of two typical toroidal vortexes of the mean flow. But, in the same time, velocity measurements revealed, that the melt flow is turbulent with $Re = v_{ch}R/u \sim 10^5$ and the amplitude of velocity oscillations is comparable with the time averaged flow velocity magnitude $|v'_{max}| \geq |v_{ch}|$. Also, the presence of low-frequency flow oscillations was exposed: most intensive of them are located close to the crucible wall between the main vortexes and have the characteristic time period about 8-12 seconds depending on inductor current (Figure 3). Pulsations with shorter period (about 1-2 seconds) can be observed as well. The major oscillation frequency f increases in dependence on the time-averaged velocity: $f \sim v_{ch} \sim I_{ind}$.

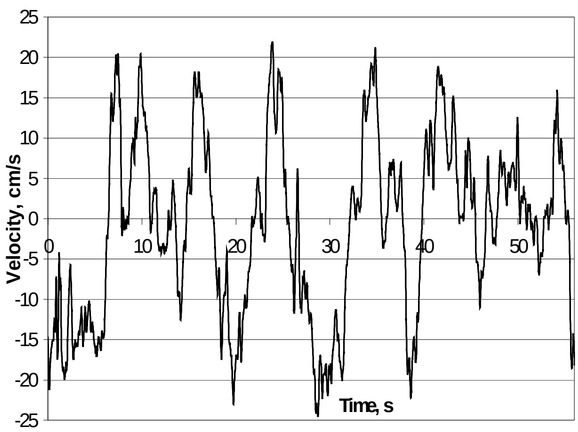

Figure 3: Axial component of the melt flow velocity oscillations measured in experimental ICF in the region between the dominating flow eddies near the crucible wall (P ~ 55 kW)

The experimental investigations of the melt flow and temperature distribution in the induction furnace with cold crucible (IFCC), presented in this paper, were performed using 6 kg pure aluminum (99.5%) in the cold crucible with a radius of 7.8 cm and a height of 26 cm. The output power of the generator was 200 kW at the frequency range 8-10 kHz. The meniscus height reached up to ~22.5 cm under those conditions. With these process parameters the meniscus shape of the melt surface is quite stable and therefore it is possible to perform detailed investigations of the free melt surface itself, the temperature field and the turbulent melt flow.

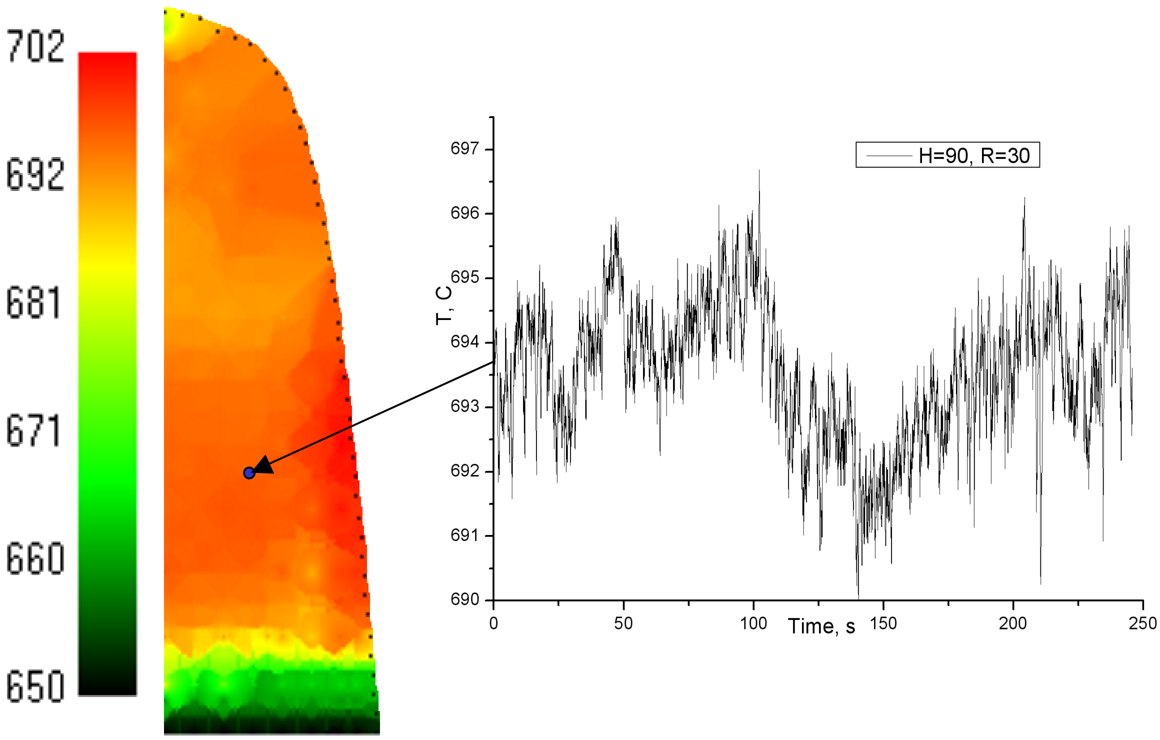

Figure 4: Temperature distribution (left) and local temperature fluctuations (right) measured in aluminum melt in the IFCC [°C]

The temperature distribution was measured using NiCr-Ni thermocouples, which were placed in a protective ceramic tube to avoid their destruction in the very aggressive aluminum environment during long-lasting experiment. However, due to this protection, the thermal inertia of the thermocouple was quite long (~2.8 s), therefore, it was possible to measure only time-averaged temperature values. The time-averaged temperature field as it was measured is shown in the Figure 4 on the left hand side. The lowest temperatures are at the water-cooled bottom, where was detected the solid skull layer with thickness about 10 mm. Also the radiation losses from the free surface lead to the formation of relatively cold area at the top. And the highest temperatures are observed in the intensive inductive heating region. The temperature distribution in the rest of the melt is more or less homogeneous.

In order to investigate temperature oscillations in several characteristic points of the melt, the thermocouple was used without ceramic protection. In this case the response time became approximately 0.8 s, but the operational time for one thermocouple decreased to the 10-15 minutes. One example of the local temperature fluctuations measured in the center of the melt region are shown in Figure 4 on the right hand side. Obtained temperature oscillations can be compared with the results of the transient 3D modeling using Large Eddy Simulation (LES). The very long-period temperature changes, which are visible on that graph (Figure 4), can be explained with unstable thermal regime of the entire melt, e.g. when some part of the skull become melted and mixed with other material. And, if we apply the high-pass filter to those data, then oscillations amplitude is within range of 1-2 degrees.

NUMERICAL MODELING

For the numerical investigations of the turbulent melt flow as well as the heat and mass transfer two turbulence models were applied. The first was the well-known k-ε model, which has relatively low mesh requirements and is widely used and verified in various numerical engineering applications. This model usually produces fast good quantitative results for the time-averaged velocity distribution in case of stationary two dimensional calculations, but fails to describe correctly the heat and mass transfer quantities in the melt when the system contains at least two dominating re-circulating flow eddies. The main reason is that k-ε equations are unable to describe low-frequency pulsations, which arise due to the large scale flow dynamics and furthermore, the discussed k-ε model is based on the hypothesis of isotropic turbulence, but experiments show, that significant anisotropy takes place not only close to the crucible walls.

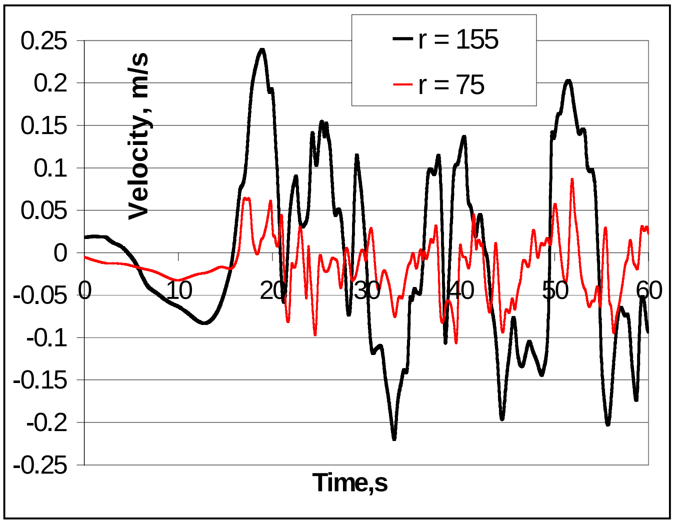

Figure 5: Axial velocity oscillations in the ICF calculated with LES turbulence model

Numerical investigations with 3D LES turbulence model revealed flow instabilities similar to those observed in the experimental induction crucible furnace (Figure 3). In order to investigate the reliability of these results, up to two minutes of the flow development were calculated after refining the mesh. Examining results, it was found out that axial flow velocity component oscillates with the amplitude of approximately 20 cm/s near the crucible wall in the region of vortexes interaction (Figure 5), but at the half-radius of the crucible these oscillations are approximately two times less intensive. The main oscillations, which have period about 10 seconds, are combined with less intensive high frequency ones, like in the experiment. The amplitude of these oscillations remains the same for different mesh resolution levels and coincides with experimental data.

INDUSTRIAL APPLICATIONS
INDUCTION CRUCIBLE FURNACE

The simulation of the turbulent melt flow in an industrial crucible furnace is presented here as one of our LES numerical investigations. This furnace has a melt volume of about 0.9 m^3 at 100% filling level. The radius of the crucible furnace is about 0.49 m and the height of the inductor is 1.34 m. The furnace is used for melting grey cast iron, which has a density of 6,800 kg/m^3. The three-dimensional hydrodynamic model consisted of about $7\cdot10^5$ elements and the time step in the transient calculations was 10^{-2} s. Industrial crucible furnace differs from the experimental installation with significantly larger linear dimensions, higher EM forces density and noticeable free surface deformation.

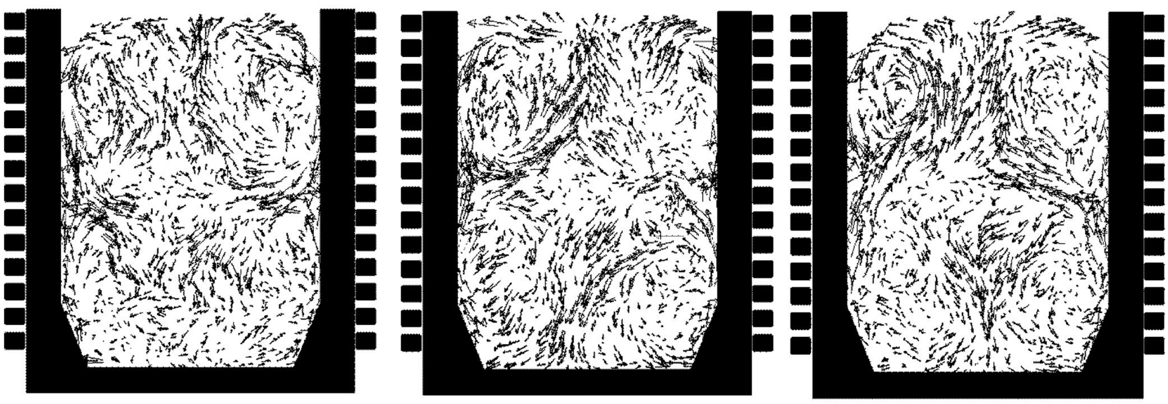

Figure 6: Velocity distribution in the industrial furnace calculated three dimensional in-stationary with LES after 20 (left), 21 (centre) and 22 seconds (right)

The comparative analysis of LES and experimental data from model furnace allowed applying this numerical method also for industrial scale installations, and qualitatively similar phenomena was achieved. The period of the low-frequency oscillations became smaller – 2 seconds – because of significant increase of the rotational velocity of the flow eddies in accordance with the hypothesis concerning inertial waves [5]. Initially axial symmetri-cal flow pattern becomes fully three-dimensio-nal (Figure 6), but considering the time-ave-raged situation the symmetry of the flow pattern remains.

INDUCTION FURNACE WITH COLD CRUCIBLE

The simulation of the turbulent melt flow and temperature distribution in the induction furnace with cold crucible (IFCC) using aluminum as a model melt and TiAl alloy as industrial used material should be the second example presented here. The electromagnetic field inside the crucible of the IFCC is not fully axis-symmetrical, due to the conductive slit walls. Therefore, an approximation is used for 2D distribution of heat sources and volume forces in the melt [6]. The thermal boundary conditions for upper and lower vortexes significantly differ - we have the radiation from the free surface above and water-cooled bottom below.

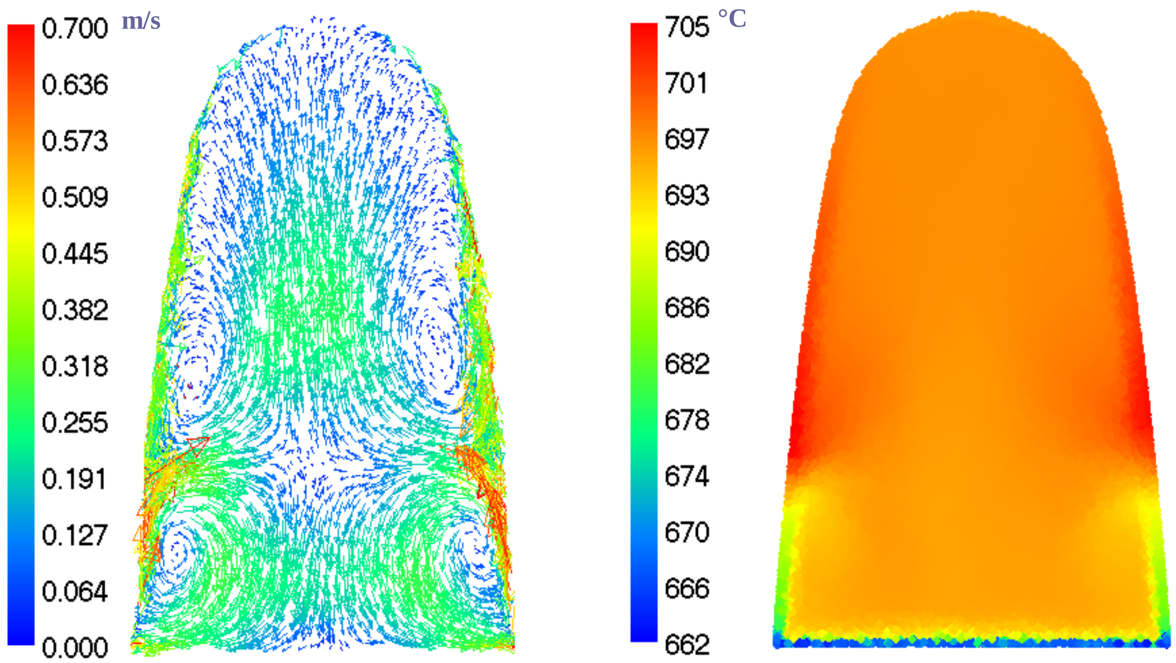

Figure 7: Time averaged velocity and temperature distribution in the IFCC with aluminum calculated with the LES model

The estimated heat flux distribution shows that only 6% of the thermal energy are lost due to the radiation. The rest of the heat is carried away with the cooling water through the crucible bottom and walls. The 3D transient calculations of the melt flow and temperature distribution are based on also on the LES turbulence modeling method. The resulting time-average velocity field (Figure 7) looks very similar to the one predicted with 2D steady-state calculations, as well as quite good agrees with experimental observations. However, 3D transient approach allows to model accurately the heat transfer processes in such flows, where two or more recirculated eddies are interacting. The calculated flow pattern at the each time-step is not symmetrical, and simulation shows, that the flow is intensively oscillating. Those oscillations provide convective heat transfer mechanism, which is possible to simulate numerically only using transient three-dimensional calculation techniques. The time-averaged temperature distribution calculated with LES (Figure 8) is more homogeneous, than in case of 2D modelling and resembles the measured temperature field (Figure 4). In the pictures series with temperature field at the consequent time-steps it can be observed how relatively cold melt masses from below penetrate into upper vortex area and are dissolved there.

The 3-dimensional numerical investigations of TiAl melting process produced similar results in terms of flow pattern (Figure 8), although the meniscus height in this case is lower due to the increased density of the material. The flow velocities are slightly higher (average velocity at r = 0 is about 55 cm/s), therefore the temperature distribution

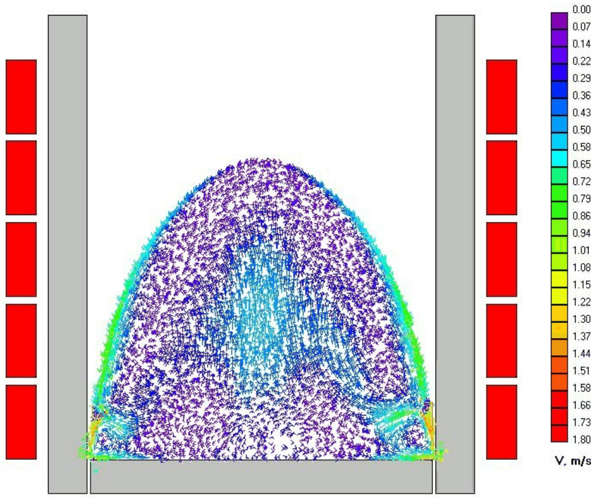

Figure 8: Time averaged velocity in the IFCC with TiAl alloy calculated with the LES model

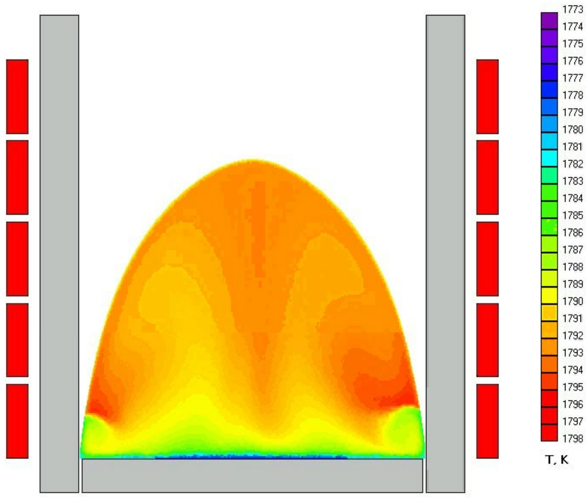

Figure 9: Time averaged temperature distribution in the IFCC with TiAl alloy calculated with the LES model

is more homogeneous, than in aluminum (Figure 9). Due to the noticeably higher R/H ratio of the melt shape, the low-velocity zone exists in the middle of the bottom region, which may lead to the thicker skull layer above the water-cooled base. Therefore, the modification of the crucible's geometry or load is considered as a possible way to improve the efficiency of the process.

CONCLUSIONS

Intensive numerical studies concentrated on applying the Large Eddy Simulation (LES) model for turbulent melt flows in induction furnaces were done together with experimental investigations in a model induction crucible furnace and an induction furnace with cold crucible. The comparative analysis shows a good coincidence between the numerical and experimental results not only in terms of mean flow, but also for the turbulent fluctuations and their kinetic energy. The studies reveal that the low-frequency velocity oscillations play a main role in convective heat and mass transfer when flow structure contains two or more large vortexes of the mean flow. The modelling results show, that only the 3D transient LES is able to model correctly the heat and mass transfer processes in these re-circulating flows. Therefore, the correct estimation of the characteristic parameters of these oscillations applying the LES method leads to creation of a universal and reliable numerical method, which can be used for solving fluid dynamics and thermal problems in practical metallurgical applications.

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